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FINAL REPORT

GENERAL DYNAMICS
Convair Division

CASD-NAS-76-020

BOSCH CO₂ REDUCTION SYSTEM DEVELOPMENT

FINAL REPORT

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April 1976

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SUMMARY

Development of a Bosch process CO_2 reduction unit was continued, and, by means of hardware modifications, the performance was substantially improved. Benefits of the hardware upgrading were demonstrated by extensive unit operation and data acquisition in the laboratory. This work was accomplished on a "cold seal" configuration of the Bosch unit (Reference 7).

The most important improvement was substitution of a ceramic recuperative heat exchanger in place of the metal one previously used. As a result, heat exchanger temperature effectiveness was raised to 0.97 and the new material showed no reactivity or degradation of any kind after more than 1700 hours of operation. This is evidence that heat exchanger life is no longer a limiting factor on Bosch unit life.

Another modification was incorporation of a cylindrical, non-reactive shield between the cartridge and the reactor shell, together with a purge gas flow between the shield and the shell. The reactor shell is thereby protected from contact with hot, reactive, recycle gases. Testing of a few hundred hours duration has shown the expected protection when purging with H_2 , CO_2 , or a mixture of these process feed gases. Further testing is expected to show that reactor shell life is extended to many thousands of hours.

Efficiency of the compressor motor was increased by operating it on reduced voltage. This, together with the improved heat exchanger effectiveness, has reduced the total electrical power input to an average of 45 watts/man.

Some new catalyst configurations were used successfully, including steel wire screen cylinders, and some combinations of steel wool with steel wire screen. Advantages sought with the screen material were more compact storage than for steel wool, and greater dimensional precision for the catalyst package.

Total Bosch unit operating experience now exceeds 10,600 hours. The technology is near the maturity required for space applications.

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1. INTRODUCTION

The overall objective of this program has been to advance the technology of the Bosch process to the level required for direct application to a manned spacecraft mission. Early in the 1960s, the potential of the Bosch process for closing the oxygen loop was recognized and some of the development efforts of that time are reported in References 1 and 2. That work, which revealed more challenges than solutions, was followed later in the decade by a research and development program that has been nearly continuous up to and including the effort reported herein.

The technical status at the start of the current contract period is reflected in the report for the preceding period (Ref. 7) and in this brief review. The problems of a high-temperature metallic seal at the reactor and vacuum jacket closures had been circumvented by a design, referred to as the "cold-seal" configuration, in which flange temperatures were low enough to allow use of elastomeric seals. The latter are very effective and have an almost unlimited life. The cold seal design also eliminated the need for opening the vacuum insulation jacket for cartridge exchange. Electrical power consumption had been greatly reduced by improved vacuum maintenance, recycle flow utilization, and heat exchanger performance. Some approaches to further reductions were identified analytically but not proven. The physical and chemical phenomena of reaction initiation were sufficiently understood to provide confidence in consistent, timely starts. Materials for high-temperature components did not exhibit the desired durability. Metals that were adequate structurally tended to become reactive after a few thousand hours. Containment of the carbon formed within the cartridge was excellent. Adequate catalyst support to prevent gravity-induced slumping was not consistently achieved. Satisfactory controls for recycle gas composition, reactor temperature, and process rate had been demonstrated.

The primary objective of the current period was to overcome materials deficiencies through materials selection and/or configuration changes. In particular, the cold-seal reactor allows more flexibility in the choice of construction materials since gas-tight joints and differential thermal expansion problems in high-temperature areas can be avoided. This makes incorporation of ceramics in critical areas much more practical than in previous configurations.

The approach was to design a full-scale, four-man Bosch unit, reusing some components of the preceding unit. New components included an Inconel 625 reactor shell, a ceramic heat exchanger, ceramic cartridge end caps, Vycor and copper heater jackets, and reactor wall shields.

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2. CURRENT UNIT DESIGN DESCRIPTION

The current unit is referred to as the "breadboard reactor" in recognition of design characteristics which make it relatively easy to change the reactor shell and internal components. This unit also has external feed, recycle, and control components which are quite accessible for changes. This flexibility for development purposes can also be of advantage in an operating unit for maintainability purposes.

2.1 GENERAL CONFIGURATION

In Figure 2-1, the recycle and control section shows in the foreground; and the large vertical cylinder in the background is the "high temperature section", which consists of the reactor and heat exchanger enclosed within a vacuum insulation jacket. The arrangement of the high temperature section somewhat separated from the recycle and control section illustrates another desirable flexibility. The two sections could be close-coupled, if desired, or they could be separated by several meters distance. The connections between consist of wiring and several relatively small tubing runs for gas flows. The vertical orientation of the reactor axis was chosen for ease and simplicity of the cartridge exchange operation in earth's gravity environment. In a space-craft application, orientation of the reactor axis can be independently chosen to conform with whatever criteria may apply.

The arrangement of components is also influenced by the flow sequence, which is illustrated schematically in Figure 2-2. This is unchanged from the previous unit except for addition of a reactor shield purge flow which is described later in Section 3.3.

The unit was sized for a nominal four-man rate, which corresponds to processing four kg of CO_2 per day, and for a 5-day cartridge exchange cycle. Dimensions and volume of the high temperature section are dominantly affected by the 20 man-day capacity, and to a lesser extent by the process rate. Volume of the recycle and control section is only slightly affected by process rate and not at all by man-day capacity. Some dimensional and volume flexibility is available through changes in arrangement and packaging density.

2.2 CHARACTERISTICS OF COLD-SEAL DESIGN

The cold-seal concept is simply that the reactor closure with seal is at the opposite end of the high-temperature section from the heat source so that the heat conduction path is long. The long path, together with low thermal conductivity and a small heat path area, results in low heat transfer to and low temperature at the flanges of the closure. The measured temperature near the seal is typically about 322°K (120°F), which is easily within long-life capability of elastomeric seals. A conventional O-ring has been used and the results have been fully satisfactory.

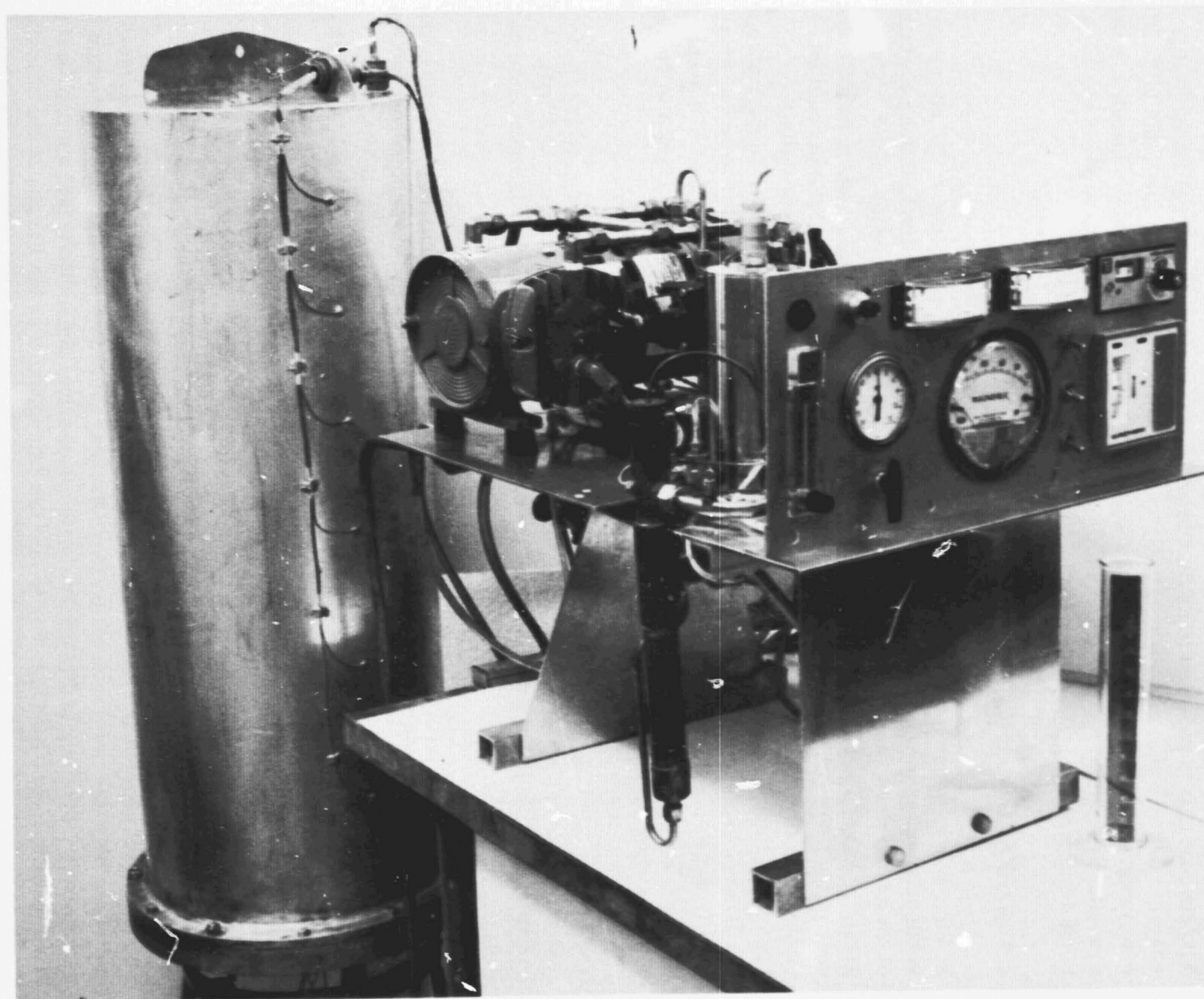


Figure 2-1. Breadboard Reactor Unit

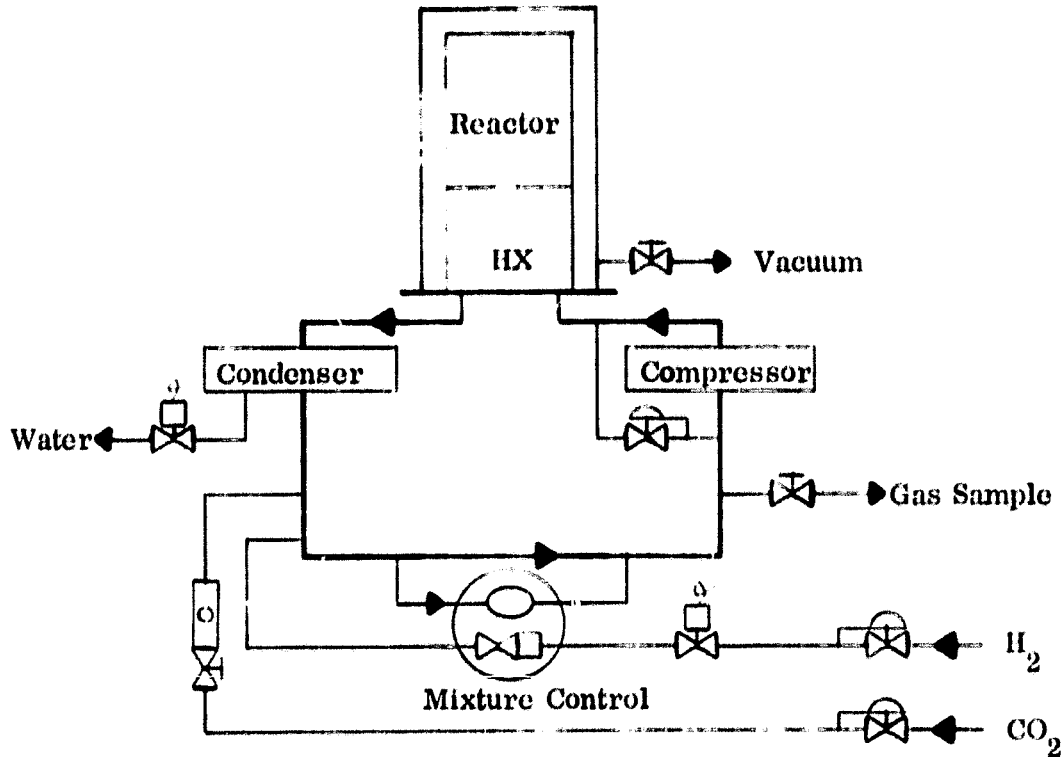


Figure 2-2. Bosch Unit Flow Schematic.

Another characteristic of the cold seal design is that opening and closing the reactor for cartridge exchange does not involve opening the vacuum insulation jacket. Figure 2-3 is a schematic section view illustrating the arrangement of flanges and seals on the vacuum jacket and reactor shell such that they can remain attached to each other while being removed from the base. Removal of these two components exposes the interior of the assembly, giving access to the shield, cartridge, heater shroud, and heat exchanger.

2.3 REACTOR SHELL

The reactor shell is critical in three respects: (1) it must have structural capability at the reaction temperature of about 920°K (1200°F) to withstand an internal pressure relative to the vacuum exterior of about 138 kN/m² (20 psi); (2) it must have low thermal conductance so that heat flow from the hot end to the cold end is minimized; and (3) the interior surface must be non-catalytic and non-reactive over a long life. The initial reactor shell of Inconel 718 (Ref. 7, p. 11) failed by excessive carbon deposition and metal degradation, principally at a welded seam. That shell was replaced after 3115 hours use by one of Inconel 625, since this material had performed well in specimen tests (Ref. 7, p. 39). Carbon deposition on the new shell was worse than for the replaced one, which led to installing the copper shield shown in Figure 2-3

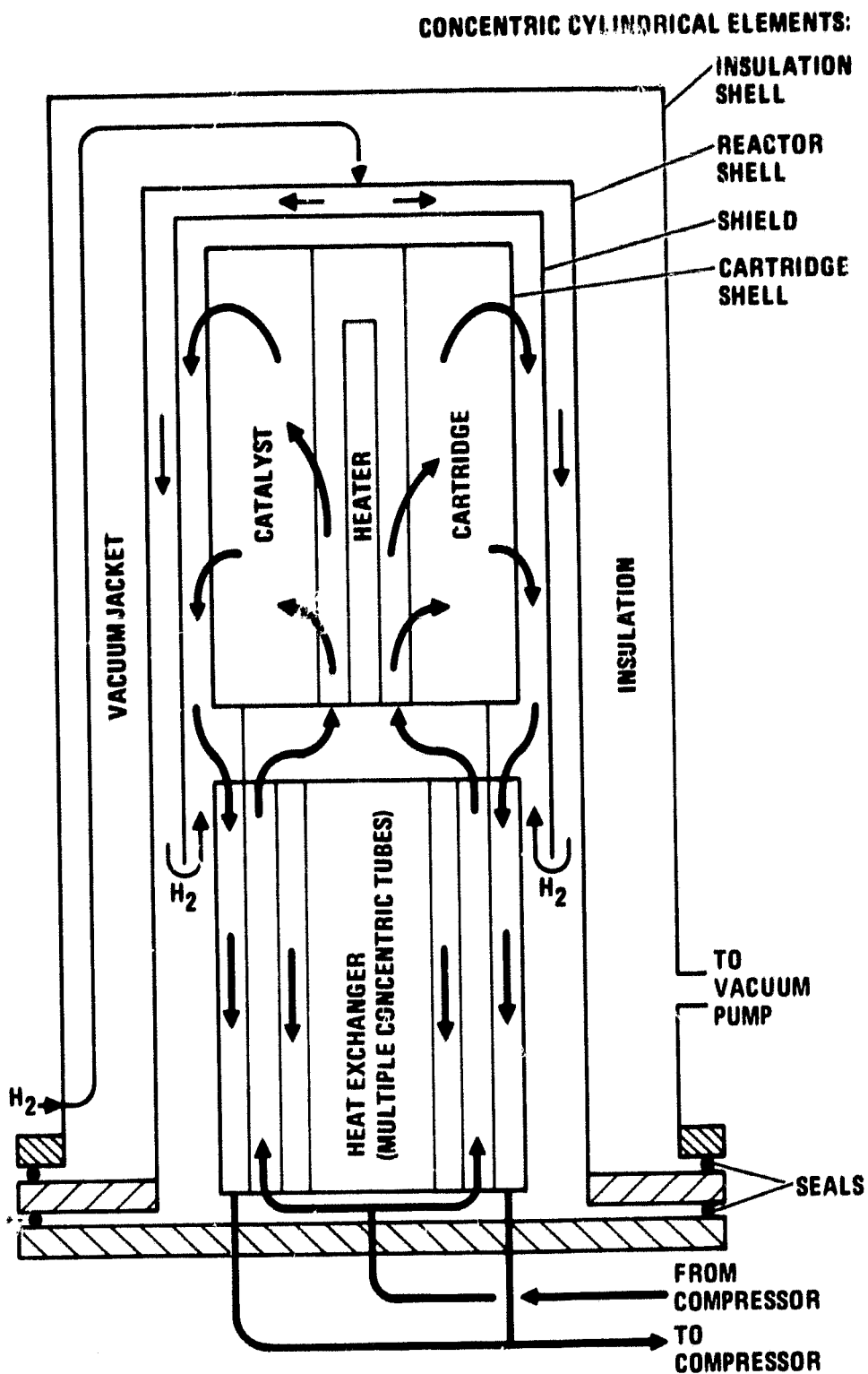


FIGURE 2-3. Bosch Reactor Section Schematic

to protect the high-temperature end of the reactor shell interior from reactive gases. Both Inconels were satisfactory as to strength and thermal conductivity. Figure 2-4 is a drawing to scale showing the reactor shell and other components of the high-temperature section.

2.4 CERAMIC HEAT EXCHANGER

The impetus for design of a ceramic heat exchanger resulted from experiences of unsatisfactory life with all previous ones made of various metal alloys. Their deficiencies included carbon deposition and/or structural failures brought on by extended exposure to the severe environment of high temperatures and reactive gases. The opportunity for design with ceramics arose from the cold-seal configuration.

The basic design concept is that recuperative heat transfer takes place in a set of 30 vertical concentric tube pairs which are uniformly spaced 12° apart on a circle of about $3/4$ the reactor radius. The gas flow through the heat exchanger is shown schematically in Figure 2-3 and the scale relationships are illustrated in Figure 2-4. The nominal tube sizes are specified by the manufacturer in inch fractions. The outer tube is $7/16$ in. (1.111×10^{-2} m) OD and $5/16$ in. (7.938×10^{-3} m) ID, which provides a $1/16$ in. (1.588×10^{-3} m) wall thickness. The inner tube has an OD of $1/4$ in. (6.350×10^{-3} m), thereby leaving a radial clearance between inner and outer tubes of $1/32$ in. (0.794×10^{-3} m) for gas flow. Each inner tube has four longitudinal flow passages of $1/16$ in. (1.588×10^{-3} m) diameter.

The inner tubes pass through and are sealed to a ceramic manifold block at the upper (hot) end, and the inner and outer tubes are epoxy bonded to an aluminum header plate at the lower (cold) end. The header and base plate enclose the manifold passages with ports through the base. Both manifolds are identified in Figure 2-4, and Figure 2-5 is a drawing of the upper manifold.

Except for the aluminum manifold and base plates at the cold end, all materials of the heat exchanger are ceramic. The tubes are of Mullite, which had previously been evaluated by exposure tests (Ref. 7, p. 39). Spacers were bonded onto each inner tube to maintain uniform radial clearance for gas flow between the inner and outer tubes. These spacers are short longitudinal segments of quartz thread, bonded with Sauereisen No. 1 paste, which is a high temperature cement for ceramics. The insulating ceramic manifold and spacer blocks are of a fused silica foam by Glasrock. The manifold block, of "Foam 50," has a density of 800 kg/m^3 (50 lb/ft^3) and a thermal conductivity at 533°K (500°F) of 0.173 watt/m K ($1.2 \text{ Btu-in/hr-ft}^2 \text{ }^\circ\text{F}$). The spacer blocks, of "Foam 30," have a density of 480 kg/m^3 (30 lb/ft^3) and a thermal conductivity at 533°K (500°F) of 0.13 watt/m K ($0.9 \text{ Btu-in/hr-ft}^2 \text{ }^\circ\text{F}$).

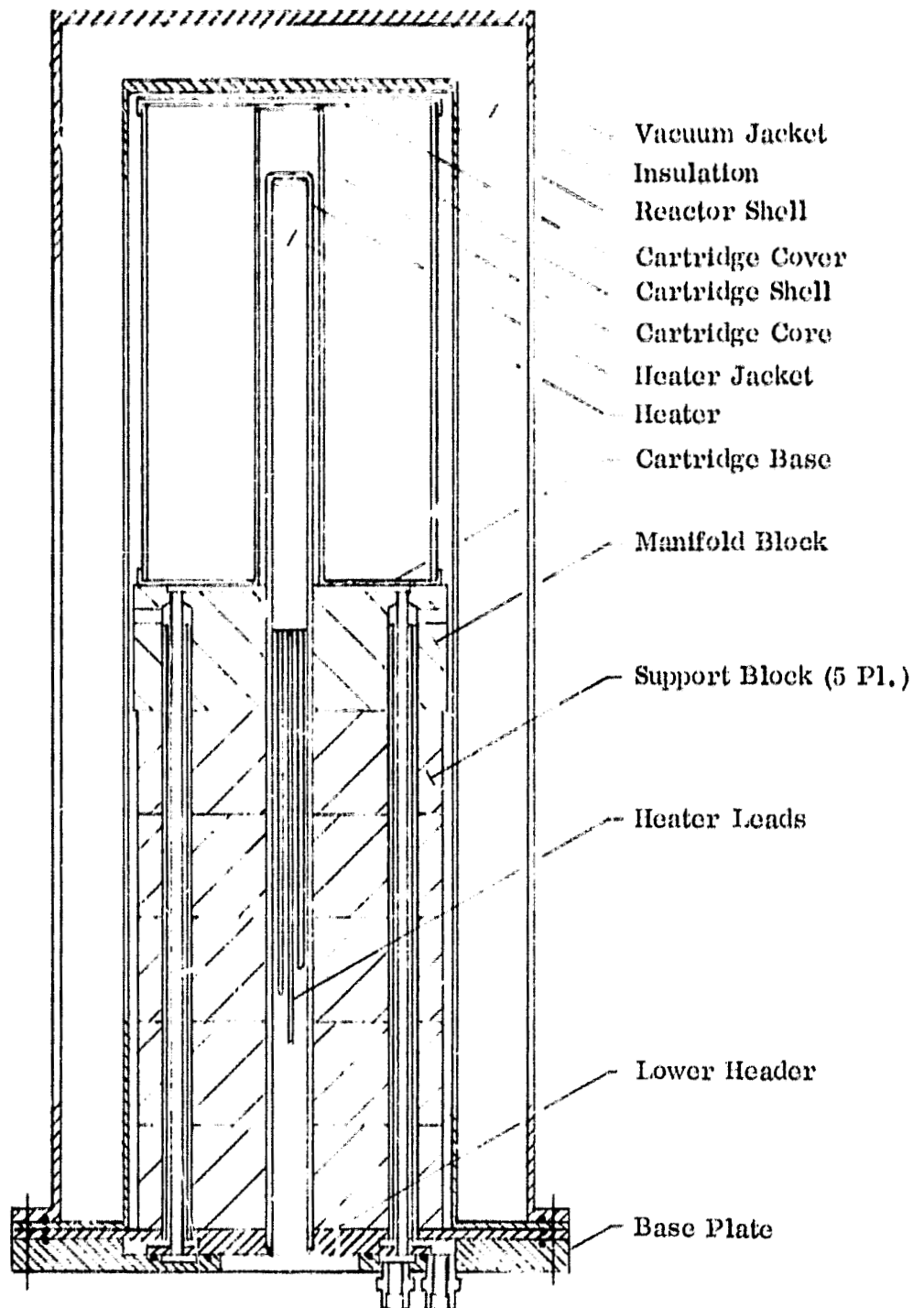


Figure 2-4. High Temperature Section

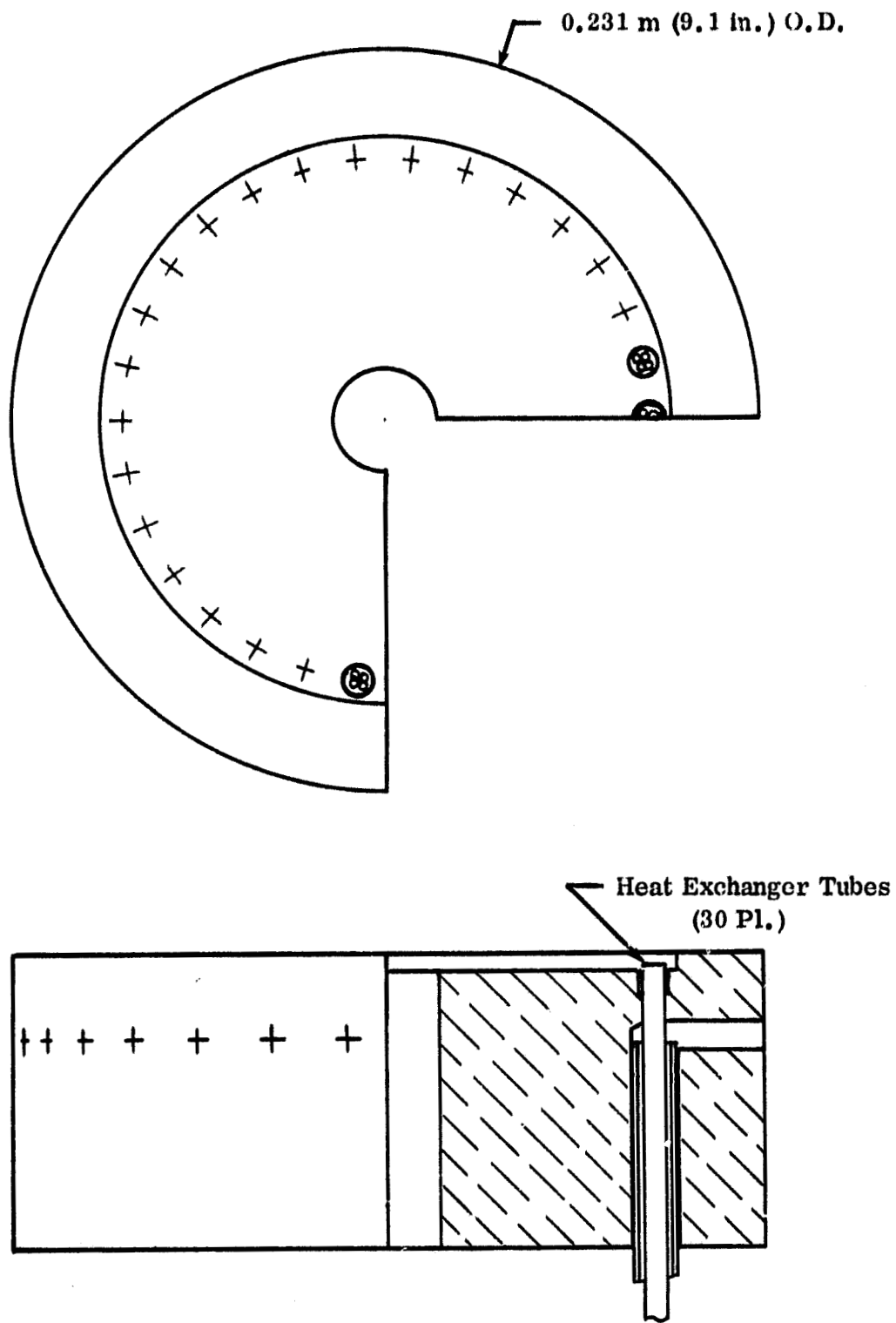


Figure 2-5. Ceramic Heat Exchanger Manifold Block

2.5 OTHER COMPONENTS

Previous reports (Ref. 4, 6, & 7) have described other components which were re-used in the current unit. In brief, the vacuum insulation jacket contains multiple layers of reflective metal foil as thermal radiation barriers, which are separated by thin blankets of quartz fiber (Ref. 7, p. 11). The recycle and control section has a motor-driven compressor, a condenser/water separator, and controls for process rate, reactor temperature, and feed mixture (Ref. 7, pp. 12-14). The mixture control modulates H_2 feed in response to sensed thermal conductivity (hence H_2 content) of the recycle gases. The process rate control is based on process rate response to recycle flow rate. The control is a pressure regulator in a bypass line from compressor discharge back to compressor intake. If, for example, process rate declines from the set point, the continued feed of H_2 and CO_2 causes a pressure rise at the compressor intake. The control responds by reducing flow through the bypass line and increasing flow through the reactor, thereby causing correction in the process rate. The schematic relationship of these components is shown in Figure 2-2.

The original H_2 feed flow route was changed to the configuration shown in Figures 2-2 and 2-4. This is a protective purge flow directed between the shield and the reactor shell internal surface to exclude reactive gases from high-temperature areas of the reactor shell. The H_2 is first bubbled through water so that the water vapor picked up will enhance the protective ability. A measurement of the water thus used is made so that it can be subtracted from total condensate yield to provide data of actual product water. Subsequently, similar feed flow route changes were made to enable purges by CO_2 and by mixed CO_2 and H_2 .

The catalyst cartridge was modified with the objective of longer life. The original metal end caps of aluminide-coated type 304 stainless steel (Ref. 4, Sec. 5.4) had failed by becoming reactive. One was restored by stripping and electroless plating with copper, but its life was short. Additional end caps were made of an unfired cast ceramic material called Thermosil Castable 120. The cylindrical shell is of 6.35×10^{-4} m (0.025 in.) gage perforated type 304 stainless steel with electroless nickel plating. It is of a "wrap-around" configuration; that is, instead of a longitudinal seam or fastener, there is about a 1/3 turn overlap of the sheet. When used with the metal end caps, the flanges thereon retain the shell and prevent excessive expansion due to carbon growth pressure. When used with the ceramic end caps, which do not have comparable flanges, two Inconel 625 bands retain the shell.

3. TECHNICAL DISCUSSION

As noted in Section 1, the various components were evaluated for performance, life, and influence on overall unit performance with greatest emphasis on those characteristics considered significant for improved performance and longevity.

3.1 CATALYST

For reasons which are discussed later, the catalyst materials used have been No. 3 steel wool, common steel wire window screen, and some combinations of these two. The term "catalyst assembly" will be used to designate a selected quantity of the catalyst material which has been formed into a desired shape and distribution and may be held in position by various accessory devices. The catalyst assemblies have not always shown adequate performance. Three general types of deficiency have occurred. The first is slow starting of the reaction even though temperatures, mixture, and recycle flow rate are all in the normal range. This phenomenon may arise from causes other than the catalyst itself. The second deficiency type is failure to attain normal process rate unless forced by abnormally high recycle flow. Forcing is undesirable because it increases both compressor and heater power requirements. The third type is premature decline in process rate unless forced. Many observations of the attendant circumstances have led to a set of requirements and constraints that at least have pragmatic value.

This discussion should begin with description of a "normal" test run, which for the current unit is 5 days operation at a nominal 4-man process rate. The operation starts with loading the catalyst assembly into the cartridge and loading the cartridge into the reactor. After reactor closure, air is purged from the system and it is refilled with a CO_2/H_2 mixture in proportions resulting from the normal setting of the mixture control. Gas recycle flow is initiated by starting the compressor, the electric heater at the core of the cartridge is turned on, and the coolant supply to the condenser is started. As temperatures rise, various gas reactions occur, forming first CO , then CH_4 , and finally H_2O and carbon. A "start" refers to identifiable and sustained production of carbon and water, while "starting period" is the total time from switching on power to a cold unit until the normal process rate occurs. Duration of the starting period is a characteristic of each reactor design, and for the unit described herein it is about two hours. With continued operation, carbon accumulation in the cartridge will cause a gradual increase in pressure drop through the cartridge. By the end of the fifth day, the increases in pressure drop, recycle flow, and electrical power consumption will reach levels indicating that efficient operation will require a cartridge change. Typically, the power level will increase only about 5% above average during the first four days, but will climb sharply to about 30% above the four-day average during the last day. Operation beyond 20 man-days is possible but would be considered "forcing".

The manner in which the catalyst assembly may contribute to events of a run depends on both physical and chemical characteristics.

3.1.1 CATALYST PHYSICAL CHARACTERISTICS. The physical properties of significance include surface area, total catalyst mass, structural strength, and distribution. Since the catalyst is expendable, the minimum mass use rate is desired. Observations have been that the surface area is not particularly relevant to starting, but is a factor in acceleration of reaction rate and, in fact, whether the normal process rate can be attained. The desired reaction acceleration favors finely-divided materials such as fine grades of steel wool. A very coarse material would require excessive mass in order to expose enough surface area. As discussed later, though, fine fibers have some disadvantages. There is also the constraint that a minimum catalyst mass is required in order to sustain the process rate through normal cycle life of the cartridge. If all other conditions are reasonably near optimum, 10 to 15 grams per man-day have been adequate. There is not a sharp cut-off point at which catalyst is expended and reaction ceases. Forcing, i.e., increasing recycle flow rate beyond the normal range, can extend duration of effective catalyst performance.

Distribution of the catalyst within the cartridge is fairly critical and the requirements are related to the generally radial flow direction of the gas mixture. Uniform distribution in the axial direction is required so that gas flow will not bypass the catalyst. This bypass tendency becomes more severe as continued carbon deposition causes increased pressure drop. The bypass resulting from lack of uniform axial distribution causes process rate to be low unless forced. The radial distribution, however, should not be uniform. It is better to induce carbon deposition of non-uniform density, with highest density at or near the outer circumference of the cartridge. Because of flow area relationships, this technique minimizes pressure drop through the cartridge. Minimum pressure drop is a factor in minimizing compressor power and is further of advantage in lessening bypass tendency. These factors favor catalyst radial distribution of higher density near the outer circumference.

The required structural characteristics of the catalyst assembly are an anomaly arising from operation in earth's gravity. Unless strength remains adequate throughout a run, the assembly will slump and allow excessive flow bypass. As a run continues, eventually carbon deposition becomes dense enough and strong enough to support its own weight. The most critical time is when (1) high temperature and reactions with the gases have seriously weakened the catalyst material, (2) carbon deposition has added some weight, and (3) the carbon is not yet dense enough to be self-supporting. The tendency to slump and the poor performance resulting therefrom have been more severe in the current vertical-axis reactor than in earlier ones with a horizontal axis. Obviously, operation in very low or zero-g would remove all need for resolution.

One approach is to use a catalyst material which is inherently strong enough, and another is to provide supplemental structural support. A coarse-fiber steel wool, identified commercially as No. 3, has been used because it is stronger than the finer grades. Another material used is 551×709 per m (14×18 per inch) mesh common galvanized window screen from which the zinc has been removed by an HCl etch. The remaining steel wire has a diameter of 2.54×10^{-4} m (0.010 in.). The usual technique with steel wool has been to form it into the geometry of a "muff" and provide vertical internal and external supports made from strips of coarse wire screen (Ref. 7, pp 34-35). Disadvantages are that prevention of slumping has not always been effective and the supports add nearly 50% to the expendable weight.

A satisfactory run was made with a self-supporting catalyst assembly of the window screen material rolled into a hollow cylinder, there being four spiral layers separated about 0.5 cm by V-shaped spacers of the same material. In this case, the weight was about 50% higher than the steel wool/wire support combination. Another configuration was a single-layer cylinder of the window screen, over the walls of which strands of steel wool were draped longitudinally, with approximately uniform distribution inside and outside the cylinder. The strength of the cylinder was not sufficient to prevent slumping. Better performance was obtained by using two concentric cylinders of window screen, with a 2 or 3 cm layer of steel wool uniformly sandwiched between. Both combinations of window screen and steel wool were a little lighter than the steel wool/wire support combination, but there is not yet enough experience for a confident evaluation of these options.

There appears to be a favorable pattern of catalyst reaction, disintegration, movement, and "consumption", which is attainable if the catalyst assembly has the required physical properties. The following is based on visual examination of many cartridges after the run, observing particularly whether slumping occurred, the location and size of voids, if any, in the carbon block, the carbon density distribution, and the presence and location of catalyst remnants. The advantages of initiating carbon deposition near the outer circumference has been described. As deposition radially inward continues, it is desirable that the carbon forces some catalyst fragments inward enabling exposure to fresh gas flow. It is not desirable that the catalyst become embedded in the most dense carbon where it is least accessible to gas flow. The most efficient use of catalyst occurs when the final distribution is approximately uniform and no intact (unused) fibers or wires remain at the end of the run. In general, the window screen did not fulfill these criteria as well as the steel wool but it has more potential as a material that does not require supplemental supports.

3.1.2 CATALYST CHEMICAL CHARACTERISTICS. Although a few other materials have exhibited catalytic properties for the Bosch reaction, none have performed as well as iron. Further, iron as contained in ordinary commercial grades of steel shows no disadvantages relative to iron of high purity. Since sulfur and phosphorus

are known to inhibit the reaction, it must be concluded that the quantities contained in commercial steels used were not sufficient to have a noticeable adverse effect.

Experiences have not been free of "catalyst poisoning" events due to other sources of contaminants. When this occurs, starting is slow or prevented altogether. An explanation has appeared in a report of some early studies (Ref. 8) to identify the particular chemical species in carbon deposition reactions which are catalytically active and which are inactive. Species which were found to be inactive were metallic iron (Fe), normal cementite (Fe_3C), and magnetite (Fe_3O_4); while the active species were Hagg carbide (Fe_{20}C_9) and a special form of cementite (Fe_3C) having a lower than normal curie temperature. The presence of traces of sulfur was demonstrated to cause formation and stabilization of the inactive carbide species which covered the iron surface thereby precluding carbon-deposition reactions. Once formed, the inactive carbide is stable at temperatures below 600°C (1110°F). These phenomena are consistent with other studies of the Bosch reaction (Ref. 9, 10) which have shown that the iron is an active chemical participant and is changed to a carbide.

Bosch unit operating experiences have also been consistent with the above. When materials containing catalyst poisons were used in a manner as to contaminate the recycle gas (for example, phosphorus contained in a surface coating intended to prevent reaction on a high-temperature area), reaction inhibition was evident. The results were visible in the cartridge afterward as an abnormal silvery white surface on the steel wool fibers, these being in total contrast with carbon blackened fibers which were not poisoned. Although complete poisoning has occurred, a partial effect was more frequent, in which starting was slow and full process rate was not readily attained. It was observed that the poisoning tendency could be suppressed somewhat by measures which promote rapid starts, such as providing high catalyst surface area and employing a high heating rate. The current practice is to avoid contaminants and to clean the catalyst before use by solvent degreasing and/or a brief etch in dilute HCl.

3.1.3 CATALYST CHARACTERISTICS SUMMARY. This report continues the customary usage of the term "catalyst" to designate the commercial material, such as steel wool, which is loaded into the Bosch reactor. Discussions of the chemistry usually restrict the term to mean Fe or some other metallic element. Considering the work cited above (Ref. 8), it would be more rigorous to further restrict the term "catalyst" to specific iron carbides which are active in causing carbon-deposition reactions.

With reference to what commercial material has most potential as the catalyst, there is not yet a conclusive superiority proven for either steel wool or screen material. For application in a space craft, the bulky storage volume of steel wool would be a

disadvantage relative to a compact roll of screen. Further, since steel wool is amorphous, the screen enables better geometrical accuracy which should help minimize flow bypass tendencies. Experience with screens is limited to relatively coarse wires. With choice of finer wire diameter and larger mesh, it is expected that the use rate in terms of grams per man-day should be at least as efficient as steel wool. Another candidate, with properties similar to screen, is very thin steel sheet which has been perforated uniformly to more than 50% open area.

Catalyst assembly performance has a direct impact on Bosch unit performance. The latter is readily measured in terms of process rate and the recycle flow rate (also electrical power) required to achieve that process rate. When temperature and mixture composition are correct but performance is abnormal, the catalyst assembly is most probably the principal contributor. Severe catalyst poisoning can prevent a start. Slow starts and failure to achieve normal process rate may arise from (a) partial catalyst poisoning, (b) insufficient catalyst surface area, and/or (c) improper catalyst distribution which allow flow bypass. Premature decline in process rate after initial normal performance can be due to (a) insufficient catalyst mass, (b) gravity-induced slumping which allows flow bypass, and/or (c) flow channeling caused by unfavorable carbon density distribution, which may arise from improper catalyst distribution.

3.2 CATALYST CARTRIDGE

The components of the catalyst cartridge are the shell, core, and end caps (Ref. 4, Sec. 3.2). A fundamental consideration is whether the cartridge shall be expendable, i.e., used for one run and then discarded with the carbon, or whether it shall be reusable by minor disassembly and removal of the carbon block. Experiences of this program have been with the reusable type. Cartridge design requirements are related to the severe operating environment, carbon growth pressure which mechanically stresses the cartridge, and convenience and cleanliness of the cartridge exchange operation.

A reusable cartridge need not have a life as long as the reactor. It may be considered reusable for more than one run (perhaps 5 to 10 runs) after which it may be replaced at minor penalties. Further, all components of a reusable cartridge need not have the same life. The limitation on life is normally that cartridge surfaces become reactive and carbon is deposited thereon. A precise life is not easily defined because carbon deposition may be very slight at first and become progressively more severe with continued use.

Recent operating experience has provided indications of life available with certain materials. A shell of Type 304 stainless steel with electroless nickel plating was good for 500 to 1000 hours. End caps of the same stainless steel but with an aluminide

coating lasted about 2,000 hours. One of these was refurbished after it became re-active by stripping and electroless copper plating, but failure of the plating was evident after 200 hours use. It is probable that electroless copper plating over new stainless steel would have lasted longer.

Unlimited life with respect to carbon deposition should be attainable with good ceramic materials. In the first such attempt, end caps cast and cured from Thermosil Castable 120 appeared satisfactory before use, but were found to exhibit reactive areas with carbon deposition after one run of 100 hours. Thermosil Castable 120 is supplied as a dry mixture of varying particle sizes. Tests showed that some of the particles were attracted by a magnet, which suggested that they contained iron. A second set of end caps was fabricated after separating out the magnetic particles. These caps have discolored with use but show very little carbon deposition. They are, however, relatively vulnerable to fracture. Favorable experience with Mullite in the heat exchanger tubes provides a basis for the belief that this ceramic would be satisfactory for cartridge end caps. Mullite is much more durable structurally than the Castable 120.

If the expendable cartridge concept is selected, the metal needs to stay nonreactive for only one cartridge cycle, which is now nominally 120 hours. Based on all materials experiences to date, it is believed that bare Inconel 718, Inconel 625, or Type 310 stainless steel would suffice. Other stainless steels with light electroless nickel plating should easily last 120 hours. Tests in actual use should be made before firm conclusions are drawn.

3.3 REACTOR SHELL INTERNAL SHIELD

The reactor shield concept was introduced in Section 2.3 and illustrated schematically in Figure 2-3. The purge between the shield and reactor shell was described in Section 2.5. Its purpose is to prevent reactive gases from contacting the reactor wall. Requirements for the shield are adequate mechanical strength, low thermal conductivity, and adequate life without carbon-deposition reactions in the severe operating environment. Low thermal conductivity is desired to help minimize heat transfer from the hot to the cold end of the entire assembly. Extremely long life is not vital, since the shield is light in weight and could be replaced periodically at small penalty. If an expendable cartridge shell is used (see Section 3.2), the shield could also be expendable each run. Some candidate shield materials for a more durable shield are oxygen-free copper, silicon bronze, aluminum bronze, and high-temperature glass.

It is emphasized that the shield with purge concept is a protective expedient intended to achieve long life of the reactor shell. A better solution would be a reactor shell

which inherently has long life without protection. A design with ceramics may be feasible. Another approach would be an impervious, thin cladding of copper over a metallic substrate of suitable thermal and mechanical properties. The cladding would have to be thin to prevent excessive longitudinal heat transfer. The substrate should be of adequate strength at operating temperatures, of low thermal conductivity, and compatible with the copper in thermal expansion characteristics.

The first shield to be tested was a cylinder of 5.08×10^{-5} m (0.002 inch) oxygen-free copper closed at one end and the same length as the cartridge. It was extended 0.102 m (4 inches) in length after the first run which showed some carbon deposition on the reactor wall at the base of the shield. The copper foil was used because of ready availability but numerous cracks developed in wrinkled areas showing it to be too fragile. A shield of 40×10^{-5} m (0.016 inch) Inconel 718 provided excellent reactor wall shielding.

The H_2 feed gas was initially chosen for the purge system because its volume flow rate is twice that of the CO_2 feed and variations in H_2 feed-point pressure have no effect on process rate control. However, in conjunction with an electrochemical depolarized CO_2 concentrator, the available pure H_2 is relatively limited. In this case it would be advantageous to use the combined H_2 and CO_2 mixture for shielding purge. This was done for several hours of operation with the Inconel 718 shield without detrimental surface effects or process rate control difficulties. Detrimental surface effects should not be expected in a single-pass situation since, as explained in reference 9, the CO concentration can never become sufficiently large for carbon formation.

3.4 HEATER JACKET

The heater jacket protects the heater and its electrical leads from reactive gases that would cause deterioration and carbon deposition. To assure such protection, the jacket must be sealed to the base of the high-temperature section (Figure 2-4). Another requirement is that the jacket thermal conductance should be low to minimize heat transfer to and temperature of the base.

The choice of jacket materials is restricted to those compatible with the environment of high temperature and fresh reactive gases. The first one used in the current unit was of Vycor glass and was satisfactory until inadvertently broken at the base during repair of another component. A replacement jacket was made of metal parts consisting of (1) an Inconel 625 tube extending from the lower end of the heater down through the base of the high-temperature section, where it was sealed; (2) a longer copper tube covering the heater and Inconel tube to within 1.27×10^{-1} m (5 inches) of the base and brazed at that location; and (3) a copper plug welded into the top end of the copper tube. The lower end of the copper tube was chemically milled to reduce wall thickness from the original 1.524×10^{-3} m (0.060 inch) to 2.54×10^{-4} m

(0.010 inch). The Inconel tube was for strength and low conductance. The copper tube was for protection, and the milling was to reduce the conduction heat path area. After several runs the copper was found to be cracked through at one of the milled steps. This jacket was replaced by one of Vycor glass similar to the original one but more flexibly bonded at the lower end to reduce the likelihood of breakage.

In evaluating materials concepts, the brittle nature of glass and ceramics is a disadvantage and the low thermal conductivity has mixed effects. It is advantageous only in minimizing longitudinal heat transfer. It is unfavorable for the desired heat transfer from the heater sheath to the inflowing gases, causing a higher temperature at the heater resistance elements for a given heat transfer rate. Further, a loose fit between the jacket and the heater is necessary because of differential thermal expansion, and there is added thermal resistance associated with that clearance. The transparency of materials such as fused quartz and high-temperature glass is an advantage because it enables more radiant heat transfer. In the Vycor jacket described above, this transparency was partly obscured by a light opaque deposit on the inside wall of the tube which occurred during use.

As for metals in the heater jacket application, copper is the only common metal known to resist the severe environment. The particular configuration of copper and Inconel 625 described above was in part an expedient resorted to because these materials in usable dimensions were available. If an all-copper jacket were attempted, preventing high-temperature creep would probably require a wall thickness of at least 5.1×10^{-4} m (0.020 inch), which would be excessive from the standpoint of longitudinal heat loss. Silicon bronze might be satisfactory structurally and thermally, but resistance to the environment has not been proven. Type 321 stainless steel is very close to copper in thermal expansion characteristics, which leads to the concept of a thin, impervious copper coating over the stainless steel substrate. This would be a preferred approach if integrity of the copper coating could be assured.

Thermal performance of the heater jacket is observable in its effect on time to heat a cold reactor, or in the temperature difference between the heater sheath and reactor shell during warm up. Keeping the heater sheath temperature low is desired so that heater life is not adversely affected. In this respect, the all-metal jacket was superior to the one of Vycor glass.

3.5 HEATER SHROUD

The purpose of the heater shroud is to confine incoming gas flow closely along the heater jacket for some distance axially, thereby delivering uniformly hot gas to the core of the cartridge. Otherwise, some of the flow can pass through the catalyst at

the heat exchanger end without receiving any additional heat from the heater. The environment for the shroud is about the same as for the heater jacket, requiring therefore a non-reactive material. Oxygen-free copper has been adequate. A transparent material such as fused quartz or high-temperature glass would have a slight advantage in allowing some radiant heat transfer from the heater jacket to the cartridge.

A shroud the full length of the heater has normally been used although many runs with no shroud and a few with a half-length shroud have been made. The effects on flow distribution and cartridge performance have not been established and probably vary with heater jacket configuration and catalyst packaging technique. A set of 6 runs without shroud had the same average starting period as the subsequent 6 runs with shroud. Both sets were with the Vycor heater jacket which may have obscured shrouding effects because it limited the heat transfer rate causing the starting periods to average about 50% longer than for copper heater jacket runs.

No measurements of flow distribution in the cartridge have been made. A candidate shroud development method would be to install a matrix of thermocouples in the cartridge, flow CO_2 through the unit with heater power on, and observe temperature distribution at frequent time intervals. The results should indicate the kind of shroud geometry changes that would improve flow and temperature distribution.

3.6 HEAT EXCHANGER

The most persistent problems of previous Bosch unit heat exchangers were carbon deposition and metal degradation leading to structural failures. The ceramic heat exchanger described in Section 2.4 was partially disassembled for examination after 1334 hours use and no carbon deposition or defects of any kind were observed. It was then reassembled for continued use.

The measured gas temperatures have shown this heat exchanger to have an effectiveness in the 0.96 to 0.98 range. The representative 0.97 effectiveness corresponds to a temperature difference of 14 K (25 F) between hot gas out and cold gas in. The above performance exceeds that of any previous configuration of this program. In summary, there is little room for improving performance and the only area which may be of future concern is whether the ceramic is strong enough to resist mechanical shocks which may occur in spacecraft use.

3.7 MATERIALS RESEARCH

Materials requirements fall into two general areas, the first of which has already been discussed in Section 3.1, i.e., providing an effective catalyst and avoiding

catalyst poisons. The other is to provide long-life materials of construction for components (sec. 3.2, 3.3, 3.4, 3.5, and 3.6) which operate under quite severe service conditions. These service conditions can be summarized as requirements for strength at high temperature and inertness chemically and catalytically in long-duration exposure to the hot, reactive, recycle gases. Temperatures are about 980 K (1300 F) at the heater surface, 920 K (1200 F) for the reactor shell, and only slightly lower at the high-temperature end of the heat exchanger. Stresses in the reactor shell are due to the internal gas pressure reaching about 140 kN/m^2 (20 psi) above the surrounding vacuum jacket. Stresses in the cartridge shell are due to internal pressure generated by carbon deposited therein. There is a further requirement that construction materials be amenable to fabrication methods that do not themselves violate other requirements; e.g., a weld has to be just as non-reactive as the parent metal. For some components, high or low thermal conductivity is very important (Sec. 3.4).

Materials investigations have been in four general categories: (1) Studies of the thermodynamics of chemical interactions between the reactive gas mixture and various materials, (2) experimental materials evaluation by exposing test specimens to the reactive environment for long durations, (3) observations of construction materials in actual use in the successive Bosch units that have been built and operated, and (4) observations of results of reaction-inhibiting surface treatments.

The thermodynamics studies (Ref. 7, pp 38-43) have application only to the question of reactivity, and led to the conclusion that metals which form no carbides, such as copper or platinum, would be preferred. Considering other requirements, a nickel-based alloy appeared most likely to succeed. The experimental exposure of small test specimens to a realistic environment of hot, reactive gases was done by enclosing them within an operating Bosch reactor. Of the several hundred different specimens tested, only a few survived many hundreds of hours exposure without showing failure such as hydrogen embrittlement, carbon growth, and/or metal surface degradation (Ref. 5, p 4-4; Ref. 6, pp 22, 23; Ref. 7, p. 39). The more promising materials were oxygen-free copper and a few stainless steels and Inconels. The most recent test results are generally consistent with the thermodynamics studies. Most test specimens have been metals and metals with protective coatings because they appeared more amenable to fabrication than nonmetallic candidates.

The ultimate test was to use selected materials in construction of a Bosch unit and operate the unit until a failure was evident. Except for satisfactory applications of oxygen-free copper, the results with metals did not confirm expectations from specimen tests. There were cases where an alloy appeared non-reactive in a specimen test but became reactive in actual use. Some protective platings which retained integrity in early use later failed to provide complete protection. In some cases,

weld areas became reactive first. Oxygen-free copper was non-reactive but exhibited excessive creep even under very light load. This limits its use to applications of near zero stress. Some coatings to poison surface reactivity, such as metallic lead, red lead oxide, and molybdenum disulfide, were found to provide temporary protection, but they also released enough vapor or particulate matter to adversely affect the catalyst. Success of specimen tests followed by failure of full-scale components may be due to non-uniformity of the operating environment, e.g., differences in gas composition or temperature; or due to non-uniform properties of the alloy which are not evident in a very small specimen. There is also some evidence that a non catalytic surface layer is formed on some metals and alloys under certain operating conditions.

In summary, most of the experience has been that metals which are least reactive (copper, aluminum, silver) are inadequate structurally. The best of those structurally adequate have failed after a few thousand hours. Some specific examples from the most recent operating experience are: (1) a reactor shell of Inconel 718 showed sustained carbon deposition and eventually perforations in the weld metal of a seam; (2) the present reactor shell of Inconel 625 has light but spreading carbon deposition, which was the reason for adding the copper shield; and (3) a cartridge shell of Type 304 stainless steel with electroless nickel plating has become very weak and brittle.

Successful use of metals in the severe environment is not necessarily precluded by the experiences cited. An aluminate coating is believed to be capable of protecting a stainless steel substrate if application techniques are developed which assure no surface defects. Oxygen-free copper as an impervious cladding over stainless steel should have very long life. To be used for a reactor shell, the manufacturing method would have to provide the required form while retaining integrity of the copper throughout. Any exposure of stainless steel edges to the hot gases would probably lead to failure. If drawing to sufficient depth is possible, the edges could be beyond the reactive temperature region.

Ceramics which passed specimen exposure tests have subsequently been successful in actual use. The ceramic heat exchanger (Sec. 3.6) has met all present requirements. It appears that a long-life heat exchanger is not possible with the present metals technology. Design of a ceramic reactor shell has been considered; but not implemented because of schedule and funding limitations. It is believed that the ceramics approach is feasible for such an application.

3.8 UNIT PERFORMANCE CHARACTERISTICS

Measures of performance which are significant and relevant to use in a space vehicle are the expendables rate (mass and volume), electrical power use, and heat loss rate. A hardware weight and volume summary is included.

3.8.1 EXPENDABLES RATE. The principal expendable is the catalyst and most of the operating experience has been with steel wool (Sec. 3.1). A quantity of 15 grams (0.033 lb) per man-day has been adequate when normal attention is given good distribution of the catalyst within the cartridge. Although experience with steel screen is limited, the results generally lead to the same consumption rate. Storage volumes, however, may be quite different. Steel wool as received from the manufacturer is compressed into packages or rolls having a volume corresponding to about 0.1 dm^3 (6 in^3) per man-day. The particular roll of screen recently used has a volume corresponding to 0.017 dm^3 (1.05 in^3) per man-day. It is estimated that perforated sheet in rolls could be stored in about half the volume of equivalent screen. Storage in the manner stated would require that the spacecraft crew prepare catalyst assemblies on board by cutting and forming the material. If packaged catalyst assemblies, or complete cartridges, are prepared on the ground and then stored aboard the vehicle, the volume rate corresponding to the current unit would be 0.7 dm^3 (43.5 in^3) per man-day; and that volume would be independent of whether the material within is steel wool, screen, or some other configuration. The volumes stated were calculated from cylindrical shapes and do not include a packaging density factor for fitting these shapes into rectangular compartments.

Another expendable is the cartridge liner, which consists of several pieces having a total mass of about 5 grams per man-day. The material is a low-density felted sheet of silica and alumina fibers. If stored with light compaction the required volume is about 0.02 dm^3 (1.2 in^3) per man day. The liners could be included in prepackaged catalyst assemblies or complete cartridges.

There are other options with respect to cartridge expendables, one being that the entire cartridge (shell, end caps, core tube, liners, and catalyst) may be expendable for each run. A second is that the cartridge have reusable end caps but other parts are expendable for each run. A third is that structural parts of the cartridge are reusable for a limited life such as 1000 or 2000 hours before being replaced by new parts. If design is to a 2000-hour life, the weight of such replacements is equivalent to about 3 grams per man-day.

3.8.2 ELECTRICAL POWER USE. Figure 3-1 is representative of power use in the present Bosch unit. Almost two-thirds of the electrical power goes to the heater, less than one-third goes to the compressor, and the rest is used by controls. The amounts to the compressor and heater change during a run, for reasons which are discussed below.

There are three primary factors causing heater power to vary in the manner shown. First, full heater power of 1000 watts is used only briefly when starting to heat up a cold reactor. The heater sheath temperature limit is usually reached in one hour

Run B-25, 0730/3/29/76 to 0730/4/3/76

4.2-man average process rate.

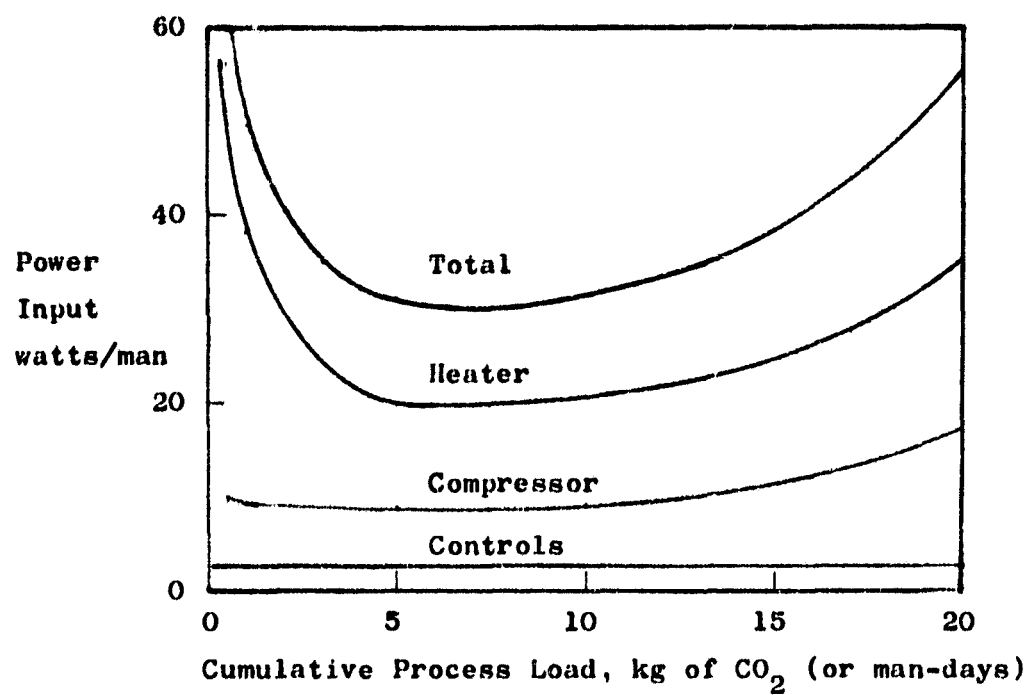


Figure 3-1. Electrical Power Use

or less, whereupon controls cause a gradual decrease in heater power. The second factor is that when a reaction starts, the contribution of exothermic heat reduces the need for electrical heat. Typically, the exothermic heat of reaction reaches a significant amount within two hours after power is turned on and reaches the full amount (110 watts for a four-man rate) within four hours. The third factor is that heater power varies almost directly with recycle flow rate, which varies generally as shown in Figure 3-2. The flow rate at the beginning of a run is made high to accelerate the reaction rate, and higher flow at the end of the cycle is necessary to sustain the reaction rate.

Power to the compressor varies with flow rate and with system pressure differential (Figure 3-2). The pressure differential varies with flow and with the amount of carbon deposited in the cartridge, leading to highest Δp and highest power at the end of a run.

The performance shown in Figures 3-1 and 3-2 represents further improvement over that reported earlier (Ref. 7). Reduction in heater power is due in part to higher effectiveness of the ceramic heat exchanger in comparison with earlier ones of metal; and due partly to improved catalyst packing and support techniques which minimize channeling and/or bypass, thereby enabling reduction in recycle flow rate. Reduced compressor power came from the reduced recycle flow rate together with a gain in motor efficiency when input voltage was lowered.

3.8.3 HEAT BALANCE. Figure 3-3 shows a heat balance for the reactor/heat exchanger/insulation jacket assembly, and was calculated from measured temperatures of the recycle gas, jacket surface, and ambient air. The gas transport heat loss is very low because the heat exchanger effectiveness is very high. The dominant loss, amounting to about 90% of input, is heat transfer from high-temperature components to ambient through the vacuum insulation jacket. During the mid-portion of a run, i.e., from 4 or 5 to around 15 or 16 man-days of a 20 man-day run, the heater power and the exothermic heat of reaction are relatively constant, each accounting for about 50% of the heat input. Consequently, if heat loss through the insulation jacket could be reduced by 50%, temperatures would be maintained on heat of reaction only, and heater power would be zero for this period. Some approaches to this level of performance are: (1) development of more effective insulation; (2) higher vacuum, as would be readily available in a spacecraft; and (3) design of higher capacity units (e.g., 12-man), which would have a lower surface to volume ratio and a lower ratio of heat loss to heat of reaction.

The heat loss to ambient represented in Figure 3-3 for the present Bosch unit is about 50 watts/man and occurs at various jacket surface temperatures in a range of about 310 to 325 K (100 to 125 F). There is an additional heat rejection of 32 watts/man into the condenser coolant, which typically has an inlet temperature in the range of 278 to 281 K (40 to 45 F).

Run B-25, 0730/3/29/76 to 0730/4/3/76
 4.2-man average process rate.

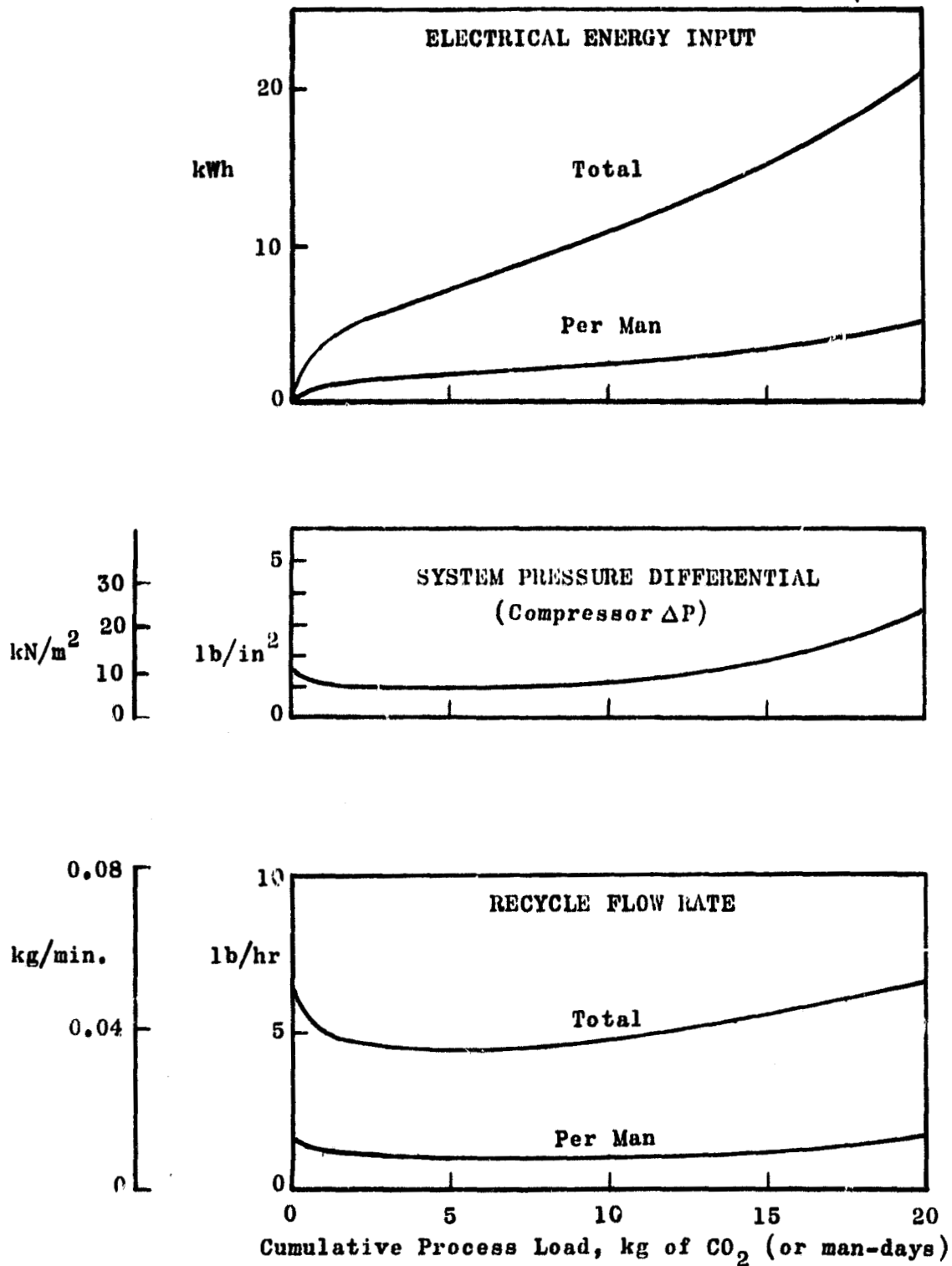


Figure 3-2. Bosch Batch Process Characteristics

Run B-25, 0730/3/29/76 to 0730/4/3/76

4.2-man average process rate.

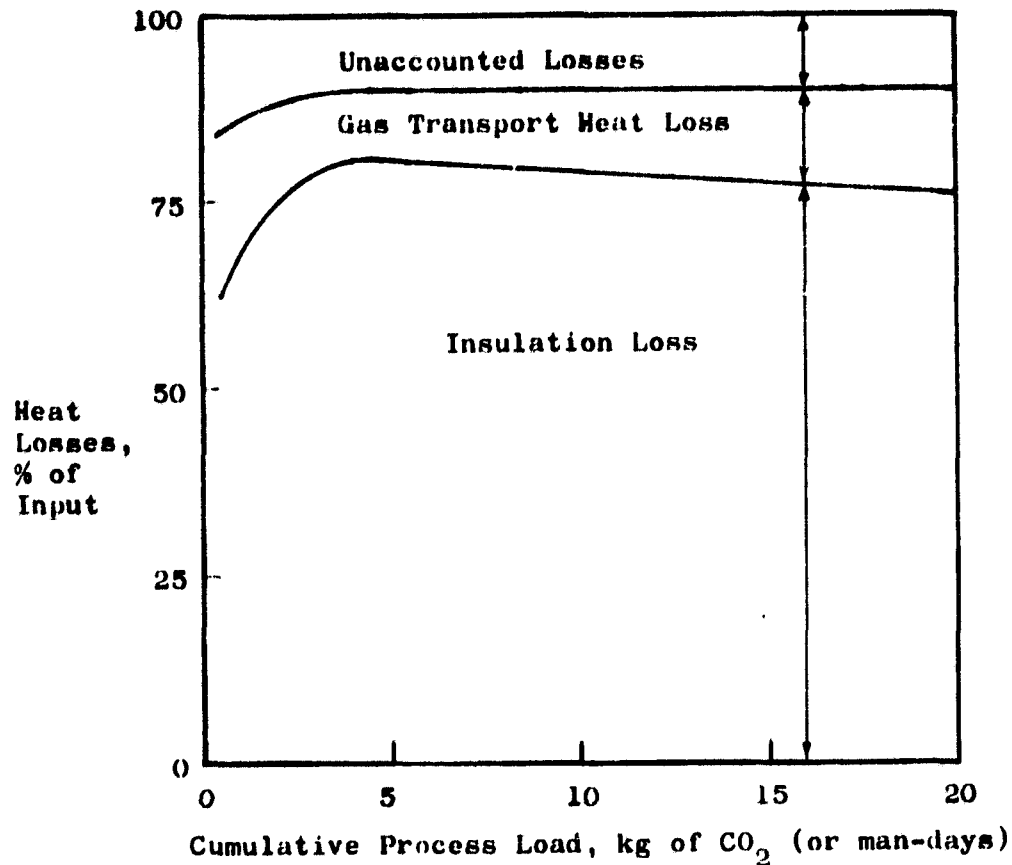


Figure 3-3. Heat Balance

3.8.4 HARDWARE WEIGHT AND VOLUME SUMMARY. Measured weights and volumes for the present Bosch unit, having a nominal 4-man rating, are shown in Table 3-1. It is estimated that a development program for space application could achieve overall a weight reduction of 50% and a volume reduction of 40% from the totals shown.

3.8.5 BOSCH UNIT PERFORMANCE SUMMARY. A summary of performance characteristics derived from the preceding sub-sections is shown in Table 3-2. This information applies to a Bosch unit sized for a nominal 4-man process rate. The energy rates per man are reasonably valid in the 4- to 6-man range. Hardware weights and volumes are for a single unit. Considering the batch process time characteristics, a minimum of two units are required. There are no allowances for additional redundancies or spare parts. The catalyst and cartridge consumables rates are essentially independent of unit capacity.

TABLE 3-1. BREADBOARD UNIT WEIGHT AND VOLUME SUMMARY

	Weight		Volume	
	kg	lb	m ³	ft ³
Control Section	30.4	67	0.17	6
High-Temperature Section:			0.11	4
Heater Assembly	1.8	4		
Base & Heat Exchanger	24.5	54		
Reactor	8.2	18		
Insulation	5.9	13		
Vacuum Jacket	11.8	26		
TOTALS	<u>82.6</u>	<u>182</u>	<u>0.28</u>	<u>10</u>

TABLE 3-2. BOSCH UNIT PERFORMANCE SUMMARY

Nominal rating	4-man
Nominal cartridge life, man-days	20
CO₂ process rate, kg/man-day	1.0
Hardware weight, 4-man unit	
Laboratory type	83 kg (182 lb)
Flight type (estimate)	45 kg (100 lb)
Hardware Volume, 4-man unit	
Laboratory type	0.28 m ³ (10 ft ³)
Flight type (estimate)	0.17 m ³ (6 ft ³)
Consumables weight, per man-day	
Catalyst	15 grams (0.033 lb)
Other cartridge components	8 grams (0.018 lb)
Consumables volume, per man-day	
Minimum*	0.028 dm ³ (1.7 in ³)
Maximum*	0.71 dm ³ (43.5 in ³)
Electrical power, watts/man	
Maximum	265
Minimum	30
Average, total 5-day cycle	45
Heat Rejection, Average watts/man	
To condenser coolant	32
To ambient	50

* See paragraph 3.8.1

4. CONCLUSIONS: MATURITY OF BOSCH UNIT TECHNOLOGY

An assessment of the maturity of the Bosch unit technology for space applications can be made. The following includes discussion of the more significant components in terms of performance recently demonstrated compared with anticipated performance attainable with further development effort.

4.1 HEAT EXCHANGER

The present ceramic heat exchanger has such high effectiveness that little is left to be achieved in better performance. Any gain in effectiveness by further development effort would merely reduce a loss that is already quite small relative to other losses. A large (e.g., 50%) reduction of the loss would have only a slight effect on overall performance. The ceramic materials have shown no reaction with recycle gases or any other deterioration with use. Ability to withstand mechanical shock will have to be considered for any space applications.

4.2 THERMAL INSULATION

In steady-state operation, heat losses through the insulation cause over 80% of the heater power required. The present insulation (Ref. 6) is not considered optimum, and improved insulation performance would be reflected directly in reduced heater power. The goal should be to sustain the process on heat of reaction only, so that steady-state heater power is zero. Development toward this goal is recommended. For example, in the present unit some of the multi-layer thermal radiation shields are of aluminum and some are silver. Polished gold foil may give better performance.

4.3 REACTOR SHELL, SHIELD, AND PURGE

The shield and purge serve the purpose of protecting the reactor shell, but they could be eliminated if the reactor shell could be made inert. No structurally satisfactory metals have been found that do not become reactive after a few thousand hours of use. Development toward a life goal of at least 10,000 hours is recommended. The more promising approaches are: (1) an all-ceramic shell, and (2) an impervious, non-reactive metallic coating (e.g., copper) over a structurally satisfactory metallic substrate. It is important to minimize heat transfer from the hot to the cold end of the shell. This requires thin walls and low thermal conductivities. Components of any multi-layer combination must be mutually compatible in thermal expansion characteristics over the maximum temperature range experienced.

4.4 COMPRESSOR AND MOTOR

Mechanical and flow losses of the compressor are assessed as already relatively

low, so that efforts to improve performance could not yield major gains. The direct-drive motor, however, is very inefficient, such that improved performance is attainable and would make an important contribution to overall performance. Custom design of a high-efficiency motor is recommended.

4.5 CATALYST AND CARTRIDGE

The concept of a pre-assembled, expendable cartridge and catalyst assembly is attractive in terms of minimizing crew effort during the cartridge exchange procedure. It is also compatible with the concept that each used cartridge with carbon will be stored in the same space vacated by a new cartridge which has just been installed in the reactor. There has been essentially no development effort toward light-weight, expendable cartridges.

A cartridge which is re-usable for several thousand hours would save some weight, but would require crew activity to remove the carbon and install catalyst. One approach is to use a pre-assembled liner and catalyst package which would have essentially the same volume and be stored in the same manner as complete cartridges. Another approach is to minimize catalyst storage volume by using rolled steel screen or very thin perforated sheet, which must then be formed by the crew into a catalyst configuration for insertion into the cartridge. There has been no development effort to optimize screen wire diameters and meshes, nor any to optimize steel sheet gauge, perforation diameters, and perforation spacings.

4.6 ZERO-G OPERATION

The water separator is the only gravity-sensitive component of the present Bosch unit. Development of a zero-g separator has not been a part of this program. Liquid/gas separator concepts which have been developed for other gravity-independent applications should be adaptable to this unit.

With regard to unit operability by the crew in zero-g, the cartridge exchange operation requires particular attention because it involves opening and closing the reactor. The present unit has a bolted flange reactor closure which performs adequately but development of a closure with quick-release fasteners is recommended.

REFERENCES

1. Remus, G. A., Neveril, R. B., and Zeff, J. D., "Carbon Dioxide Reduction System", Report No. AMRL-TDR-63-7, Contract No. AF33(616)-8223, MRD Division, General American Transportation Corporation, January 1963.
2. Armstrong, R. C., et al., "Life Support System for Space Flights of Extended Time Periods," NASA CR-614, Convair Division of General Dynamics, San Diego, CA, November 1966.
3. Holmes, R. F., Keller, E. E., and King, C. D., "A Carbon Dioxide Reduction Unit Using Bosch Reaction and Expendable Catalyst Cartridges", NASA CR-1682, Convair Division of General Dynamics for NASA Langley Research Center, November 1970.
4. Holmes, R. F., King, C. D., and Keller, E. E., "Bosch CO₂ Reduction System Development", Interim Report, Contract NAS8-27276, Report No. GDCA-DBD73-001, Convair Division of General Dynamics for NASA Marshall Space Flight Center, January 1973.
5. King, C. D., Russ, E. J., Girouard, H. D., and Chiarappa, D. J., "Oxygen Regeneration/Reaction Control Systems Concept Study", Interim Report, Contract NAS8-27276, Amendment 2, Report No. GDCA-DBD72-003, Convair Division of General Dynamics for NASA Marshall Space Flight Center, December 1972.
6. Holmes, R. F., North, B. F., Keller, E. E., and Russ, E. J., "Bosch CO₂ Reduction System Development", Interim Report No. 2, Contract NAS8-27276, Report No. CASD-NAS-74-018, Convair Division of General Dynamics for NASA Marshall Space Flight Center, August 1974.
7. Holmes, R. F., King, C. D., and Keller, E. E., "Bosch CO₂ Reduction System Development", Interim Report No. 3, Contract NAS8-27276, Report No. CASD-NAS-75-030, Convair Division of General Dynamics for NASA Marshall Space Flight Center, July 1975.
8. Berry, T. F., Ames, R. N., and Snow, R. B., "Influence of Impurities and Role of Iron Carbides in Deposition of Carbon from Carbon Monoxide," Journal of the American Ceramic Society, Vol. 39, No. 9, September 1956.

REFERENCES (CONT.)

9. Meissner, H. P., and Reid, R. C., "The Bosch Process", MIT, ASME paper 72-ENAV-9, Environmental Control and Life Support Systems Conference, San Francisco, CA, August 14-15, 1972.
10. Manning, M. P., and Reid, R. C., "Carbon Dioxide Reduction by the Bosch Process," MIT, ASME paper 75-ENAS-22, Fifth Intersociety Conference on Environmental Systems, San Francisco, CA, July 21-24, 1975.